Fundamental Concepts in the Design of the Flying Spot Store

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The flying spot store is a semipermanent information storage system developed for use in an electronic switching system which utilizes cathode ray tube access to information stored on photographic emulsion. Parallel optical channels are used to provide high capacity and parallel readout. A feedback system provides rapid and precise beam positioning for writing and readout. This paper describes the fundamental design considerations for memory systems of this type, stressing physical realizability, speed, capacity and other system features. The characteristics of a laboratory model are presented.

I. INTRODUCTION

1.1 *Application in Electronic Switching Systems*

The flying spot store has been developed to meet the needs in electronic telephone switching systems for high capacity semipermanent memory arranged for rapid random access to stored words. In its present form the flying spot store meets all the requirements of the system described elsewhere in this issue.[1] The original suggestion for the use of a flying spot store was made by C. E. Brooks, leading to the development described in this paper.

Electronic switching systems of the future will also require memory of this type. Directory-to-equipment number translations alone will require millions of bits. In the form now under development, the flying spot store appears capable of meeting the memory requirements of these large systems.

1.2 *Form of the Flying Spot Store*

In the flying spot store information is stored as a pattern of transparent and opaque spots on developed photographic emulsion. Access

for writing and reading is gained by means of a number of light beams generated by a single cathode ray tube and an array of objective lenses operated in parallel, each imaging the working area of the cathode ray tube face on a separate photographic area. A photomultiplier detector is located behind each area. One bit of each word is placed at the same address position, on each of the storage areas. In the laboratory model described each of these areas is on a separate photographic plate. A single access operation, i.e., beam positioning, therefore results in readout of a number of bits in parallel. In the usual instance, this number can be made equal to the word length.

Beam position is controlled by a closed-loop feedback system developed especially for this purpose. A number of the parallel optical channels contain code plates. The bar patterns on these code plates are chosen so that readout from these channels gives the cartesian coordinates of the beam position at all times in parallel binary form.

An error signal is derived by the comparison of this position readout with the required address position in a parallel digital comparator. The signal is applied to integrating and deflection amplifiers in tandem to drive the beam to within one spot diameter of the required position. Once within this area, the beam is locked by linear servo action to the single code-plate edge passing through the center of the cell at the address selected.

1.3 *Early Work on Photographic Storage Systems*

The basic idea of light-beam access to information stored on photographic emulsion is not new. It has been known for a long time that storage densities as high as 10^6 bits per square millimeter can be obtained on emulsions.[2] With the incentive of low-cost high-capacity memory, many proposals were advanced in the literature for light beam access systems. King, Brown and Ridenour describe many of these proposals in an early survey article.[3] These early systems used only one source, objective lens and photodetector, and differed principally in means of access. Access was provided either by positioning a cathode ray tube beam or by mechanically addressing the point on the storage plane between fixed light source and detector.

Systems using the cathode ray tube or flying spot scanner type of access offered the possibility of rapid random access. However, in proposed systems of this type, the cathode ray tube and lens were operated at extremely high resolution in order to provide enough total capacity to make the system useful. This imposed requirements upon the devices,

upon mechanical positioning tolerance and particularly upon the beam-positioning system which were extremely difficult to meet.

Systems using mechanical selection in whole or in part offered the possibility of high capacity but suffered from the slow sequential access dictated by the mechanical addressing arrangement.

For these reasons, neither type of system could have been used to satisfy the memory requirements of the electronic switching systems of the type now being developed.

1.4 *The Analog Accuracy Problem*

All of the early proposals for the flying spot scanner type of access recognized the severe difficulty in obtaining the required analog accuracy in beam positioning. In addition, our studies have shown that it is desirable to position the reading beam within ± 0.1 spot diameter of the center of the written spot. Less precise positioning would degrade the discrimination ratio or force a reduction in capacity. In an analog beam positioning system used to establish an array of 500×500 spots at the cathode ray tube, the accelerating voltage supply for the cathode ray tube and the deflection amplifier power supply would have to be regulated to within ± 0.02 per cent to maintain this position accuracy. Similar close requirements would appear at many other points in the system.

For these reasons, it has been a fundamental premise that beam positioning would be controlled by a closed-loop system in which the final positions for the cathode ray tube beam would be a set of mechanical reference edges fixed in space in the same plane as the stored information. This philosophy was suggested by R. W. Ketchledge, and implemented by multiple channel techniques in the first complete storage systems developed by R. E. Staehler and R. C. Davis.[4] A system of this type overcomes many of the difficulties in open-loop analog systems and makes the flying spot store type of system feasible.

1.5 *Purpose and Organization of the Paper*

This paper describes the fundamental design concepts and mode of operation of the flying spot store type of semipermanent memory system. The first section deals with physical realizability and shows that a wide variety of stores can be built. The succeeding sections discuss speed, capacity and other features and advantages resulting from parallel channel organization and the use of closed-loop beam-positioning systems. The characteristics of a laboratory model of the flying spot store are given.

We have attempted to include enough detail so that the interested reader can proceed directly from this to other future papers which will describe in detail the advances in systems, circuits, devices and measurement techniques which have made the flying spot store possible.

II. FUNDAMENTAL DESIGN CONCEPTS

2.1 *Physical Realizability*

We turn first to a discussion of the physical realizability of a single-channel system like that shown in Fig. 1. This discussion is pertinent since the flying spot store is made up of many parallel single-channel systems. The major advances and improvements of the flying spot store depend upon our ability to operate many of these channels in parallel from a single cathode ray tube.[4]

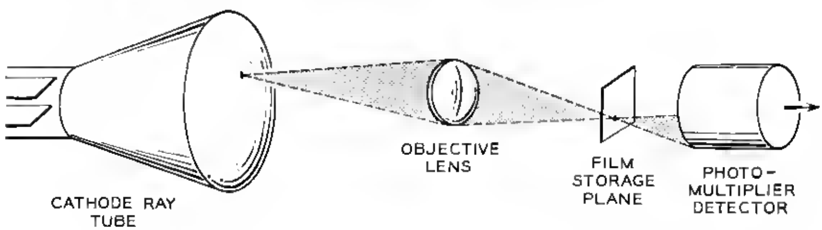

Fig. 1 — Single-channel photographic storage system.

At the start of the flying spot store project, work was begun on physical measurements of the properties of the devices used in the single-channel system: cathode ray tube, phosphor, optical elements, photographic emulsion, photocathode and electron multiplier. Very little of the data ordinarily available on these devices was in a form useful in designing the flying spot store. This measurement work has provided the necessary data on device characteristics for designing the laboratory model of the flying spot store described in Section III as well as the later systems now under construction.

2.1.1 *Signal-to-Noise Considerations in Readout*

Fluctuations in the amplitudes of 1's and 0's read out from the store result from physical imperfections in various elements of the system and electrical noise generated in the photomultiplier. Fluctuations in the first category arise from beam malpositioning, which leads to partial superposition of information written on the plates; from halo and scattering

effects in the phosphor screen; from limited spot spacing on centers set in order to get maximum capacity per channel; and from defocusing of the cathode ray tube beam. There are local contributions to this noise due to variations in phosphor light output as a function of position, film blemishes, variations in film density, optical aberrations and lens vignetting. In the model of the store described in this paper, the cathode ray tube beam-positioning system, the spot spacing on centers, the cathode ray tube itself and the objective and condenser lenses have been chosen so that fluctuations of this type do not reduce the discrimination ratio in readout below 10:1. Discrimination ratio is defined as:

$$\frac{S_{1,\min} - S_{0,\max}}{S_{0,\max}},$$

where $S_{1,\min}$ is the minimum amplitude of a 1 signal read out from the store and where $S_{0,\max}$ is the maximum amplitude of a 0 signal. Doubtless some improvement in this ratio can be obtained in later systems by more careful design. Redundancy is introduced to correct a major portion of the errors caused by film blemishes and the errors introduced on a per-channel basis by electrical fluctuations.

Electrical noise is superposed on the fluctuations due to physical imperfections. This noise arises from shot noise generated at the photocathode and from regenerative effects in the photomultiplier. Both components are "noise-in-signal" and affect primarily the amplitude of the 1 signal. The noise current from these sources is the dominant electrical noise. This is the case since the shot and regenerative components of the output current are much greater than the component that is due to thermionic emission from the photocathode in the wideband output circuits and at the output current level used in high-speed systems. The signal-to-noise ratio could be improved by increasing the light level at the photocathode. However, it is desirable to set the light level as low as possible, since this permits the widest possible choice in the selection of components and operating conditions for the other devices in the system. These considerations are made clear by the following example which gives the operating conditions in the information storage channels of the laboratory model of the flying spot store:

If sampling time is 0.1 microsecond, output circuit bandwidth is 3.5 megacycles and $\bar{i}_{pc}$, signal component of photocathode current is 400×10^{-5} microamperes, then the shot noise component of photocathode current is given by:

$$i_{\text{shot, rms}} = (2e\Delta f \bar{i}_{pc})^{1/2} = 6.7 \times 10^{-5} \text{ microamperes.} \qquad (1)$$

Under these conditions, the equivalent photocathode current required to account for the observed regenerative noise component of anode current would be

$$i_{\text{regen, rms}} = 35.0 \times 10^{-5} \text{ microamperes,}$$

and the thermal emission component of photocathode current at 25°C is

$$i_{\text{thermionic, rms}} = 0.05 \times 10^{-5} \text{ microamperes.}$$

Thus, the thermionic component is negligible compared to the shot and regenerative noise components.

Upon combining the noise components quadratically, the total electrical signal-to-noise ratio is found to be 11:1. If the only noise were that due to shot noise the signal-to-noise ratio would be $400/6.7 = 60:1$ and the electrical fluctuations would be small compared to those due to physical imperfections.

A note about the nature of regeneration noise is appropriate here. Regeneration noise depends on anode current level and total tube gain. Recent experiments have shown that regeneration noise is associated with "after-pulsing" in the photomultiplier. Tubes of a new design have been tested which do not show after-pulsing or regeneration under the operating conditions required in use in the flying spot store. For this reason, in the discussion which follows, we consider shot noise as the limiting factor in setting the photocathode current.

2.1.2 *Flux Levels in the System*

In the preceding section we showed how the electrical signal-to-noise ratio depends upon the signal component of photocathode current, $\bar{i}_{pc}$. We now determine the radiant flux required to produce this photocathode current, and determine the flux levels throughout the system for a typical case.

2.1.2.1 *Choice of Phosphor and Photocathode.* The radiant flux required at the photocathode depends on the photocathode efficiency and on the match between the spectral sensitivity curve of the photocathode and the emission spectrum of the phosphor. All of our applications to date have used the type S-11 Cs-Sb photocathode. The region of high sensitivity of this photocathode is wide compared to the emission spectrum of most of the fast-decay phosphors.

The design objective for all systems studied has been maximum speed in access and readout. A fast phosphor is required for this purpose and type P-16 has been used in all applications. It exhibits an exponential decay, with a time constant after aging of 0.05 to 0.06 microsecond. Its

spectrum is very well matched to the type S-11 photocathode and its efficiency is the highest of any of the fast-decay phosphors we have tested. Its spectrum does not change significantly with bombarding current density or life. The emission spectrum of type P-16 phosphor and the relative spectral sensitivity curve of the S-11 photocathode are shown in Fig. 2.

2.1.2.2 *Choice of Cathode Ray Tube.* The preceding paragraph shows that the phosphor and photocathode are chosen on the basis of compatibility and on the basis of speed of operation. Similar restrictions are met in the choice of cathode ray tube and optics. For the tube the limits are well defined: Here we want the brightest possible spot (i.e., greatest flux per unit area) of a specified size. The spot size may be fixed by system

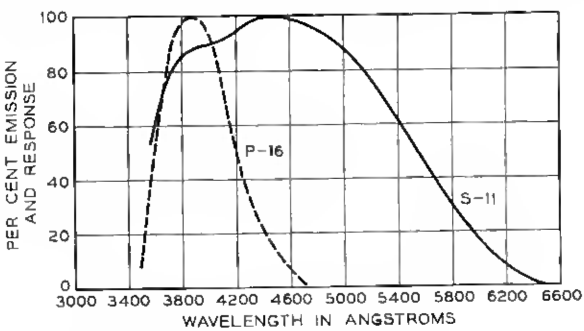

Fig. 2 — Spectral emission characteristic of type P-16 phosphor and relative spectral sensitivity of type S-11 photocathode.

requirements or device limitations. For example, system speed may dictate that there be one spot on the cathode ray tube face for each word to be stored in the memory, in order that readout can be obtained in a single access operation. This requirement, coupled with limitations on the length and diameter of the cathode ray tube which may be used, then fixes spot size. In other cases, the spot size may be chosen, along with other parameters of the system, to provide an optimum system design for a specific application. In the laboratory model of the flying spot store spot size was set by device limitations.

The maximum current density in the focused spot depends directly on cathode loading and accelerating voltage.[5] The cathode loading must be limited to a value such that good tube life is obtained. In general, we make the accelerating voltage as high as possible, since light output increases with both the total current in the beam and the bombarding energy. However, limits are set on maximum accelerating voltage by the

maximum deflection voltage which we wish to provide (deflection-amplifier power consumption sets this limit) and by the allowable phosphor loading, (watts/cm^2 to screen). In many cases the phosphor loading is the more severely limiting factor. This is easily understood because the power density at the phosphor screen may easily reach a kilowatt per square centimeter, screen weights are typically a few milligrams per square centimeter and the temperature rise of the screen with this power input is very rapid. Under such conditions, the exposure of any one point of the phosphor screen to the beam must be limited or the screen will be quickly destroyed. These factors determine the maximum total flux from a spot. If sufficient flux cannot be obtained for an intended application, either speed of operation or channel capacity must be reduced.

2.1.2.3 *Choice of Optics.* With the total flux determined by these factors, the objective lens must be chosen so that the fraction of the total light collected which reaches the photocathode produces the required photocathode current level.

Primary among the other factors that enter into the choice of optics is the effect of the lens on discrimination ratio. Since many parallel optical channels are combined in the store, the performance of the furthest off-axis lens is usually limiting. In this or any other channel the same beam initially writes, and later reads, the spots on the photographic emulsion. If the lens scatters light from the focused beam into adjacent areas of the emulsion, the spot spacing at the cathode ray tube must be made greater than that required to prevent overlap due to distribution in intensity in the source alone. Wider spacing reduces the number of spots in both coordinates of the array and reduces the total system capacity.

2.1.2.4 *Low Flux Level at Photocathode.* The fraction of the total flux which must be collected by each objective lens to provide the required photocathode current is very small, even in the highest-speed systems. For example, total flux of the order of 1500 microwatts can be obtained from each spot in a 256×256 array on a type P-16 screen operated at the phosphor loading limit. The flux required at the photocathode to produce a shot-noise-limited signal-to-rms. noise ratio of 20 to 1, with an output circuit bandwidth of 10 megacycles, is about 0.03 microwatts. Thus, the lens aperture and focal length and the system magnification ratio must be chosen so that a fraction $0.03/1500 = 1/45{,}000$ of the total flux emitted reaches the photocathode. The fraction is smaller in slower systems, with output circuits of narrower bandwidth.

The important fact that this fraction is small even for high-speed systems cannot be overemphasized. Thus, the requirement on the frac-

tion of the total flux which must be intercepted by each objective lens can be met in a wide range of optical systems. For example, D. R. Herriott has shown several designs which utilize from 36 to 300 lenses. All of these are scaled from the operating conditions in the laboratory model of the flying spot store. All keep the flux at the photocathode constant at the level found in the laboratory model. It is this favorable situation which allows us to design stores with very diverse speeds and capacities. Many of the other desirable features of the system result from the use of lenses of small aperture operated at relatively large object distances. For example, increasing the *f*/ number of a lens permits a greater depth of focus to be achieved. This results in much less severe axial positioning tolerances on optical elements, cathode ray tube and film plane.

2.1.2.5 *Energy Required for Exposure.* One additional condition must be met. The flux density in the focused beam at the film plane must be sufficiently high to get a dense spot after development with a very short exposure time. This requirement arises directly from the mode of operation, in which the entire memory plane is prepared by exposure of each spot in turn. It has been found that the flux level which produces a satisfactory signal-to-noise ratio at the photocathode, even in the highest-speed system, produces, in quite ordinary photographic emulsions, a dense written spot with exposure times ranging from a few tens to a few hundred microseconds. Thus, the exposure of several million spots requires a few minutes at most and the process is reasonable. This is another of the large number of points of compatibility enjoyed by this particular form of system.

2.1.3 *Example of Single-Channel Design*

To illustrate the preceding discussion we present a design for a typical single channel suitable for use in a flying spot store. The components and operating conditions listed in Table I have been chosen with the idea of providing a large number of parallel channels. These parameters are intended to be a typical example rather than be descriptive of a working flying spot store. However, the flux levels throughout the system and other conditions listed in Table II have been verified in laboratory experiments.

2.2 *Multiple Optical Channels*

It has been shown that one can build multiple optical channel systems which satisfy flux level, mechanical and optical requirements. This section discusses some additional aspects of multiple channel organization.

TABLE I — CHARACTERISTICS OF DEVICES FOR INFORMATION STORAGE CHANNEL

Cathode Ray Tube	
Array size:	256 × 256
Phosphor screen:	type P-16
Operating conditions:	10 kv, 10 microamperes in focused beam
Spot size:	0.025 inch
Photomultiplier Tube	
Photocathode:	type S-11
Photocathode sensitivity	≈0.04 microampere/microwatt (including effect of spectral sensitivity and phosphor emission spectrum)
Gain:	1.5×10^5
Output current:	350 microamperes (limited by dynode gain fatigue)
Output circuit bandwidth:	3.5 mc (0.1 microsecond sampling time)
Optics	
Objective lens:	6-inch, f/8.0 lens operated at 4/1 reduction
Condenser lens:	4-inch f/3.5
Absorption and scattering loss:	1/4.2 (losses in objective and condenser lens, cathode ray tube face plate and emulsion — extreme off-axis channel)

TABLE II — POWER LEVELS AND OPERATING CONDITIONS IN SINGLE-CHANNEL SYSTEM

Power in cathode ray tube beam:	10^5 microwatts
Peak power in focused beam:	250 watts/cm² max. (limiting factor)
Phosphor screen efficiency:	≈1.5%
Flux from cathode ray tube:	1,500 microwatts
Fraction of light collected by objective lens:	1/6400
Fraction of light lost by scattering and absorptions:	1/4.2
Flux at photomultiplier tube photocathode:	0.055 microwatt
Peak flux density in film plane:	885 microwatts/cm² min.
Exposure time:	≈100 microseconds
Photocathode sensitivity to emission from P-16 phosphor:	0.04 microampere/microwatt
Photocathode current:	0.0023 microampere
Shot noise limited S/N; S_{peak}/N_{rms}:	45/1
Photomultiplier tube current gain:	1.5×10^5
Output current:	350 microamperes

2.2.1 *Information Assembly and Exposure*

In the multiple-channel store one bit of each word is stored on each information storage area of the photographic plate. The information to be stored is assembled so that all the bits to be placed on any one plate

appear in sequence. The addresses of the binary 1's are then recorded on magnetic tape. Means are provided which allow the storage areas to be exposed one at a time. In writing the plates, one particular channel is selected and the position of the cathode ray tube beam is placed under the control of the information recorded on the magnetic tape. The beam is addressed to each spot of the array in turn. Opaque spots are generated by allowing the beam to dwell at a spot position for an appropriate exposure time — in the laboratory model this is approximately 600 microseconds for ordinary negative plates in which opaque spots result from exposure and 2000 microseconds where the plates' photographic image is reversed in development. The beam is swept quickly past those areas which must remain transparent. When the storage areas have been exposed, the plates are removed from the store, developed and reinserted.

2.2.2 *Parallel Readout*

In general, a number of channels equal to or greater in number than the word length can be supplied. With this organization, a single access operation (i.e., beam positioning) results in readout of the entire word in parallel. Because the access operation normally occupies much more than half of the cycle time, the time for readout of a given volume of information is minimized. This organization also eliminates the need for shift registers to assemble the parts of the word, which results in a minimum amount of output circuitry. It also affords advantages when redundancy is introduced for error detecting and correcting.

2.2.3 *Increased Total Capacity*

Multichannel stores can be built with capacities exceeding that of any single-channel store and without sacrificing speed of operation.

2.2.3.1 *Conditions on Maximum Number of Channels.* The maximum number of channels depends on the maximum off-axis angle at which the lens chosen can be used without degrading the discrimination ratio below a specified value, upon the lens aperture and object distance (distance from lens to cathode ray tube screen), and upon the maximum flux available from the spot on the cathode ray tube screen. The off-axis angle and object distance determine the area of the lens plane which may be used. The number of lenses which may be placed in this area depends upon the lens aperture and, because of the restriction that the image areas must not overlap, on the magnification ratio. This means that the magnification ratio is usually less than one and decreases as the number of channels is increased. However, the effect of

film blemishes might become serious at very high storage densities, and this may become an additional limit on magnification ratio. For a given limiting angle, the usable area in the lens plane increases with the reduction in magnification ratio, so this additional requirement does not conflict with the growth in number of channels.

If we assume that the magnification ratio is fixed by one of the preceding requirements and focal length is fixed by the over-all length of the system, then the solid angle in which lenses may be placed increases and the solid angle subtended per lens decreases, with increasing $f/$ number. The maximum number of channels is proportional to this ratio and grows strongly with increasing $f/$ number.

2.2.3.2 *Effect on Array Size and Resolution.* All the changes which increase the number of channels do so at the expense of a reduction in resolution at the cathode ray tube. This reduction is made necessary by two factors. First, it is usually not possible to obtain the same resolution in wide off-axis positions as is obtained on axis. Second, the changes in the optical system which permit us to realize a large number of channels reduce the fraction of the light collected by each objective lens. If the light level at the photocathode and, as a consequence, the electrical signal-to-noise ratio and speed of operation are to remain constant as N is increased, the flux at the cathode ray tube must be increased. Since the cathode ray tube is usually operated with phosphor loading as a limitation, this increase can only be obtained by increasing the spot size. Since the over-all size of the cathode ray tube remains fixed, this forces a reduction in the number of spots in the array.

2.2.3.3 *System Capacity.* System capacity is given by $C = NR^2$, where N is the number of channels and R is the number of spot positions in one row of the cathode ray tube array. As we change from a single on-axis channel to a multiple channel system, N increases and R decreases. However, R falls much less rapidly than $1/\sqrt{N}$, so that the total system capacity increases strongly with the number of channels.

As the number of channels is increased the magnification ratio must eventually be reduced to avoid overlapping images. Likewise, off-axis operation tends to reduce the resolving capability of the lens. Finally, increasing the number of channels reduces the flux available to each lens, both because of the reduced effective aperture in the off-axis positions and because of the reduced solid angle subtended by each lens. These factors tend to require either larger spot size at the cathode ray tube to increase the available flux or wider spot spacing to hold the discrimination ratio constant. Thus, increasing the number of channels tends to force a reduction in the number of spots used on the cathode ray tube

screen. However, this reduction is small enough to permit the total system capacity to continue to grow strongly with increasing number of channels.

The system may be scaled according to number of channels, system capacity and speed remaining constant. If, for example, the beam diameter is doubled the flux available is increased by a factor of four, and the number of spot positions in the cathode ray tube array is reduced by a factor of four. This increase in flux permits us to use a lens of one-half the aperture of that in our original system, so that four times as many lenses can be accommodated within the same area of the lens plane.

2.2.4 *Independence of Bits of Stored Word*

The parallel-channel arrangement is well suited to the introduction of redundancy for error checking and detecting. If only one bit of each word is placed on each storage area in the film plane, a film blemish, regardless of size, can affect at most one bit of the stored word. Use of the Hamming code[6] then makes it possible to detect and correct one or more independent errors of this type. In this case, the information to be stored would be encoded in Hamming single-error-correcting, double-error-detecting code, with the check and correction features extending over the Hamming bits. These bits would be read out as part of the word and are available at once when needed.

There are virtually no interactions between the remote storage elements of one storage area or between the various channels.

2.2.5 *Optical Beam Encoding*

The availability of multiple optical channels makes it possible to use some of these channels in the optical beam encoder, which is the sensor element of the closed-loop beam-positioning system. It will be shown that very considerable advantages accrue to the system as a whole through the use of this type of sensor element.

2.3 *Servo Control of Cathode Ray Tube Beam Position*

2.3.1 *Description of Beam-Positioning System*

The feedback beam-positioning system is shown in block diagram form in Fig. 3(a). Since the positioning systems for the two deflection directions are identical and independent, only one is shown.

Beam positioning involves both the digital selection of a single storage cell and the precise positioning of the beam at the center of this cell.

These precise positions, as well as the binary coordinates of the cell, are established by the pattern on the code plates located in the same plane as the stored information. Each code plate occupies one channel of the system. Its associated lens forms a line image on the code plate of the spot ou the cathode ray tube face. Patterns on the code plate are chosen so that the readout from the photomultipliers in these channels gives the beam coordinate in parallel binary code. This section of the system is termed the optical beam encoder.

In the first step in beam positioning, the position readout from these code plates is compared with the required position (address) in the digital comparator. This comparison yields an error signal which is applied to the integrating and deflection amplifiers in series to drive the beam to the desired position.

The simplest form of the comparator generates an error signal of the

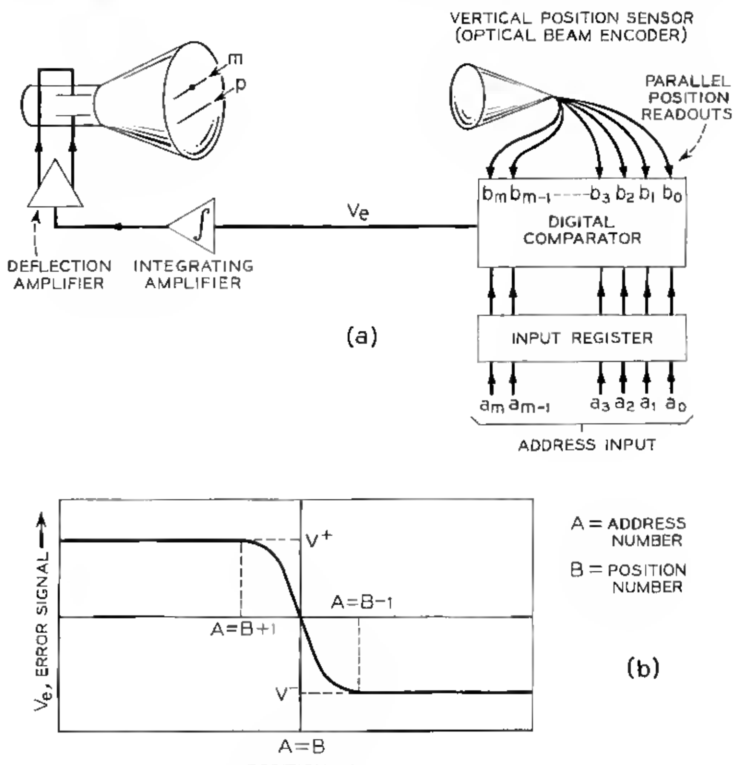

Fig. 3 — (a) Feedback beam-positioning system; (b) error signal as a function of position.

form shown in Fig. 3(b). The output has a constant positive value, V^+, when the beam is more than one full cell above the desired address and an equal negative value, V^-, when the beam is more than one full cell below the desired address. This particular type of comparator is known as the "sign-only" comparator. Comparators which yield sign and approximate magnitude of error have also been built and are being studied. This discussion is confined to the sign-only type, since this illustrates the important system features.

Once the beam is within the correct cell, the error signal becomes a continuous monotonic function of position, passing through zero precisely at the center of the cell. This error signal is generated by the passage of image of the beam across the transparent-to-opaque boundary in the one code plate column which has an edge at the required position. The comparator transmits the error signal without modification to the integrating and deflection amplifiers and the beam is locked by linear servo action to the code plate edge at the center of the cell.

2.3.2 *Operation of the Feedback Loop*

The action of the beam-positioning system using a sign-only comparator can be understood by considering its response to a change in address. The beam is assumed to be at rest at vertical level m. When a new address corresponding to level p is suddenly applied to the a or address terminals of the digital comparator, the previously existing match disappears. Since p is below m on the cathode ray tube screen, the error signal jumps to the full positive value V^+. This step function applied to the integrating amplifier produces an output which increases at a constant rate with time. This output is applied to the deflection amplifier, which drives the beam downward at a constant speed towards position p. When the beam reaches the position $p + 1$, the output from the comparator and the speed of drive start to decrease. This is the beginning of the region of linear servo action.

In order to understand the action of the loop as the beam settles to the equilibrium position within this linear region, we must consider the open-loop frequency response curve of the system. This is an integrating type of response with high constant gain from dc to a low-frequency break point. Above the break point the gain falls at 6 db per octave. The unity gain point occurs at a high frequency, typically 500 kc. To insure stability and a well-damped response in settling, the loop gain frequency response is shaped for 3 to 4 octaves beyond the frequency of unity loop gain. Because of the finite dc and low-frequency gain, the

loop exhibits integrating behavior only for transient changes. After sufficient time, a step-function input results in a constant displacement by an amount corresponding to the dc loop gain, rather than a constant speed.

When the beam reaches the position $p + 1$ the magnitude of the signal from the comparator starts to decrease towards zero and the speed of drive diminishes. The beam actually comes to rest at the point of zero output voltage from the comparator only in the center of the raster. For all other positions the beam is off-centered by a small amount. The off-centering is just sufficient for the comparator output voltage, which is amplified by the full low-frequency gain of the integrating and deflection amplifiers, to maintain the beam deflection to the edge selected. Typically, the open-loop dc gain is very high and signals of $0.1V^-$ or $0.1V^+$ are sufficient to deflect the beam to steady-state positions at the raster edge. The dc gain is made high so that all transfers will be completed within the initial 10 per cent of the ultimate response of the integrating amplifier to the step-function input from the logic. Within this region the voltage output increases linearly with time and the beam moves at constant speed.

Although the full low-frequency loop gain is not needed to establish the readout position (readout is done before the beam settles to the accuracy guaranteed by the dc loop gain), the gain is available to oppose any perturbation imposed on the system. Thus, in a system already operating, 60 db of feedback opposes all changes occurring with frequencies up to 300 cycles per second and 20 db of cancellation is available at 50 kc. Therefore, the system is much less sensitive to electrical pickup and mechanical vibration. This is one of the important advantages gained for the system by the use of a closed-loop beam-positioning system.

2.3.3 *Speed Considerations*

The speed of positioning is of major importance. In this section we shall show the factors which limit the maximum speed of operation in systems using the sign-only digital comparator mentioned previously. We shall also discuss the conditions which determine the time to settle to the readout position within the selected cell. It will be seen that these two factors are related.

There is a well-defined maximum speed with which the beam may enter the linear region and settle without overshoot or with small overshoot. If this is exceeded by a small factor, oscillatory behavior results. In systems using the sign-only comparator the maximum slewing speed

in the region more than one cell away from the match location is set by this requirement.

From the preceding discussion, we can see that both the slewing speed and the time to settle from the edge of the cell depend on the loop frequency response. The maximum crossover frequency (frequency of unity loop gain) which can be realized depends on the asymptotic gain characteristic of the loop. The asymptotic characteristic is steep because of the relatively large number of stages in the loop. In a typical loop design, amplifier and logic stages contribute 6 db per octave to the asymptotic slope above 8 or 10 mc, the effect of the finite persistence characteristic of the phosphor is seen as a 3-mc frequency cutoff, and the photomultiplier tube output circuit contributes one cutoff above 800 kc. Thus, in a typical loop, the asymptotic slope may reach 48 to 60 db per octave above 8 megacycles. The situation is further complicated in that the transit time around the loop contributes excess phase shift which cannot be equalized. This delay amounts to approximately 0.1 microsecond in the systems built, and seriously reduces the phase margin at high frequencies. Because of the steep asymptotic characteristic and excess delay phase, it is helpful to introduce a flat gain step in the frequency response below unity gain in order to preserve stability and insure a well-damped settling response.

One loop now in use has a loop crossover frequency of 500 kc. The maximum slewing speed is three spots per microsecond. The settling time to within 0.1 spot diameter of the final position is 0.8 microsecond.

2.3.4 *The Optical Beam Encoder*

The concept of the use of the optical beam encoder in the beam-position servo system was developed by C. W. Hoover, Jr. One version is shown in Fig. 4. The pattern on the code plates can be chosen so that the readout is in any desired binary code. Gray code (reflected binary) is normally used in the flying spot store. The code plate edges which occur at the transitions from each number to the next are used as the reference edges to which the beam is locked by linear servo action.

2.3.4.1 *Coupling Between Cathode Ray Tube and Film Plane.* In an earlier section it was noted that high loop gain is available to oppose the effects of external perturbations. Since the code plates are located in the same plane as the stored information, a valuable coupling is introduced between the reading spot of light on the cathode ray tube face and the written information on the code plate. Thus, in the case of vibration, the cathode ray tube might move but the reading spot of light would

remain fixed in space with its projected image on the written spot, as long as the position of the code-plate edges remains fixed with respect to the written spot. Likewise, movement of the image plane as a whole would not cause beam malpositioning.

2.3.4.2 *Frequency Cutoffs and Time Delay in Encoder.* Since the encoder forms part of the feedback loop, its gain and delay characteristics are important. Frequency cutoffs encountered in the encoder are the transit time cutoff of the cathode ray tube deflection plates, the cutoff due to the phosphor persistence characteristic and the dispersion cutoff of the photomultiplier and the photomultiplier tube output circuit. The transit time cutoff of the deflection plates and the effective dispersion cutoff of the multiplier occur above 100 mc. Thus, they contribute virtually no phase at or near the frequency of unity loop gain and can be excluded from the asymptotic characteristic in this region. The effect of the phosphor persistence can be represented by a 3-mc frequency cutoff. The other important cutoff is found in the photomultiplier tube output circuit. The output resistor is chosen to give a voltage swing of about 3 volts to operate the digital comparator with fatigue-limited maximum output current of the photomultiplier. Typically, this resistor, with the output and circuit capacitances, results in a frequency cutoff

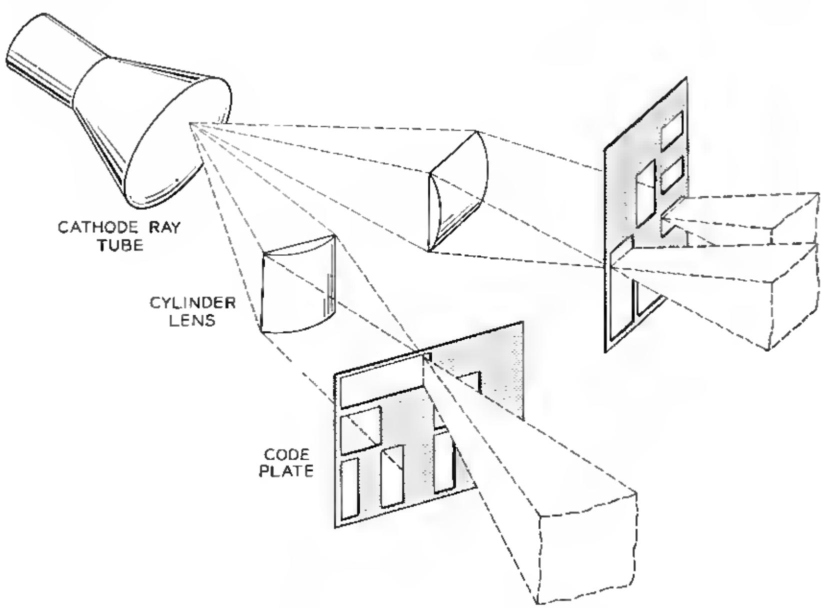

Fig. 4 — Two-axis optical beam encoder.

of about 800 kc. Thus, the optical beam encoder contributes only two important cutoffs to the asymptotic loop characteristic.

Most of the signal delay found in the loop is due to the encoder. Here are found the transit time delays because of the electron transit time from the deflection plates to the cathode ray tube screen (approximately 7 millimicroseconds), the time of flight of light in the optical path (approximately 4 millimicroseconds) and the electron transit time in the photomultiplier (50 millimicroseconds). As mentioned earlier, these delays play a part equally important to that of the open loop gain characteristic in determining the speed of slewing and settling.

2.3.4.3 *Encoding Transconductance.* One measure of the utility of an encoder is the encoding transconductance. For the optical beam encoder, considered as a unit from the cathode ray tube deflection plate terminals to the photomultiplier tube output, the encoding transconductance is defined as

$$g_{\text{enc}} = \frac{\Delta i}{\Delta V}\Bigg|_{\substack{1 \to 0 \\ 0 \to 1}}, \tag{2}$$

where Δi is the current change at the output of the photomultiplier as the beam moves from an opaque area on the code plate to a clear area and ΔV is the voltage change at the deflection plates required to move the beam from the center of one spot position to the center of the adjacent spot position (i.e., to change a "1" to a "0" or vice versa on the least significant digit code plate). The maximum change in current, Δi, is limited by the maximum current which can be drawn from the photomultiplier tube without serious fatigue. J. R. Pierce (Ref. 5, p. 142) has shown that there is a theoretical limit on the minimum possible deflection sensibility [defined as volts to move the beam by an amount equal to the spot diameter — note that this is precisely ΔV in (2) above]. This dependence is given in

$$\Delta V \geqq K \left(\frac{j_{\max}}{j_0}\right)^{1/2} V_a, \tag{3}$$

where $j_{\max}$ is the maximum current density in the beam, j_0 is the cathode current density, V_a is the potential in the deflection region and K is a constant depending on the geometry of deflection plates and focusing system. In the cathode ray tube designs for the flying spot store, the ratio of current density in the spot to the cathode current density is very nearly constant. This is because current efficiency is sacrificed for

intensity efficiency (j_{max}/j_0) in these tubes. At low current efficiency, the ratio (j_{max}/j_0) is nearly constant (Ref. 5, p. 125). Thus, we see that minimum deflection sensibility increases directly with the accelerating voltage. Therefore, to obtain maximum encoding transconductance in the encoder it is desirable to choose the minimum value of accelerating voltage at which the desired light output and resolution can be obtained. The transconductance does not increase with increasing accelerating voltage simply because the fatigue limit on photomultiplier output current prevents us from taking advantage of higher output currents due to greater light inputs to the multiplier.

A typical encoder has a deflection sensibility of 2 volts per spot and an output current of 2 ma. This yields an encoding transconductance of 1000 micromhos and should be compared with the encoding transconductances of 100 micromhos typically obtained in electron beam encoding tubes.

2.3.4.4 *Effect of Encoder on Cathode Ray Tube Requirements.* Finally, we note the effects of the use of the optical beam encoder on the cathode ray tube. Since the complete array of positions is specified hy the fixed code-plate masks, it should be possible to change cathode ray tubes, after a failure, without rewriting the information on the storage plates. In addition, the requirements on cathode ray tube deflection direction orthogonality and uniformity of deflection sensibility with position are virtually eliminated. Consider, for example, the effect of a 10 per cent change in deflection sensibility. In analog beam-positioning systems this would result in local crowding or expansion of the pattern. In the closed-loop system this merely results in a very small change in the time required for the beam to settle to its final position.

2.3.5 *The Digital Comparator*

Several types of comparator have been developed by R. W. Ketchledge. However, since our purpose is to show general principles and mode of operation we confine our discussion to the sign-only form of the comparator. This form has been termed the sign-only servo.

As a first step in the description of the comparator we note all of the special conditions placed upon it by the application. These are as follows:

1. Parallel operation. Speed dictates that the comparator operate on parallel inputs from the input register and optical beam encoder.

2. Carry from most significant to least significant digit. When the position is changing rapidly the values of the encoder digits of low significance become indeterminate. Use of a carry in the normal direction would therefore seriously limit speed.

3. Linear transmission characteristic within selected cell. For signals of magnitude less than V^+ or V^- the comparator merely transmits the error signal generated by one edge in the optical beam encoder.

4. Gray-binary comparison. The input addresses to the flying spot store are in parallel binary form. The code plates of the optical beam encoder read out the beam position in the Gray or reflected binary code. This code has the very desirable feature that one and only one digit changes in going from any one level to either adjacent one.

5. Compatibility with servo loop. The transmission and delay characteristics of the digital comparator must be such that it can be included in the servo loop without serious penalty in speed and stability. Its frequency response should be flat to well above the frequency of unity loop gain and it should contribute as few cutoffs as possible to the asymptotic characteristic. The delay should be such that the equivalent phase at gain crossover is tolerable.

Sign-only logic meeting these requirements has been built. We now turn to a discussion of the actual mechanism of number comparison.

The starting point is the following set of rules for obtaining the sign of the error between two parallel binary numbers. These are developed first for the case of binary-binary comparison and extended later for the case of binary-Gray comparison.

Consider two binary numbers, A and B, with A being the address number which remains fixed throughout the cycle of comparison and B being the position number which takes on all successive digital values in approaching A. Thus we have two numbers:

$$\text{Address, } A: a_m\,,\, a_{m-1}\,,\, a_{m-2}\,,\, \cdots\, a_j\,,\, \cdots\, a_0\,,$$
$$\text{Position, } B: b_m\,,\, b_{m-1}\,,\, b_{m-2}\,,\, \cdots\, b_j\,,\, \cdots\, b_0\,,$$

where a_m and b_m are the most significant digits, and where the first mismatch is found at the jth digit. The first mismatch determines the sign of the error. The rules are as follows:

1. Consider the pairs of digits a_i, b_i.
2. Write a third number c_i resulting from each comparison.
3. Starting at the most significant digit, write $c_i = 1$ for all matches up to the first mismatch.
4. At the first mismatch, a_j, b_j, choose c_j as follows:

$$c_j = 1, \qquad a_j > b_j \text{ (i.e., } a_j = 1, \qquad b_j = 0),$$
$$c_j = 0, \qquad a_j < b_j \text{ (i.e., } a_j = 0, \qquad b_j = 1).$$

5. Following c_j, write $c_i = 1$ for all remaining digits, if $a_j \geqq b_j$.
6. Combine the m digits, $c_m \cdots c_0$, resulting from these operations

in an m-input coincidence circuit. The output of this coincidence circuit will be 1, i.e., a coincidence resulting from an input on each of the m leads whenever $B \leqq A$. As B changes from equal to A to greater than A the coincidence disappears, and for all cases $B > A$ the output of the coincidence circuit is 0. Examples will make this clear. The m, c_i outputs go to individual leads of an m-terminal coincidence circuit.

Example 1: $B < A$

$$
\begin{array}{lcccccccccccc}
 & & & & & & i = j & & & & & & \\
a_i: & 1 & 1 & 0 & 1 & 0 & 1 & 1 & 1 & 1 & 0 & 1 & 0 \\
b_i: & 1 & 1 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 1 & 1 & 0 \\
\hline
c_i: & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1
\end{array}
$$

In this case the c_i values are all 1. Therefore the coincidence circuit output is also 1. This output drives the beam in the direction required to reduce the value of B. This is defined as a down drive.

Example 2: $B = A$

$$
\begin{array}{lcccccccccccc}
a_i: & 1 & 1 & 0 & 1 & 0 & 1 & 1 & 1 & 1 & 0 & 1 & 0 \\
b_i: & 1 & 1 & 0 & 1 & 0 & 1 & 1 & 1 & 1 & 0 & 1 & 0 \\
\hline
c_i: & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1
\end{array}
$$

Here again the coincidence circuit output is 1 and the direction of drive is down.

Example 3: $B > A$

$$
\begin{array}{lccccccccccccc}
 & & & & & i = j & & & & & & & & \\
a_i: & 1 & 1 & 0 & 1 & 0 & 1 & 1 & 1 & 1 & 0 & 1 & 0 \\
b_i: & 1 & 1 & 0 & 1 & 1 & 1 & 1 & 1 & 0 & 1 & 0 & 0 \\
\hline
c_i: & 1 & 1 & 1 & 1 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 1
\end{array}
$$

In this case comparison of the c_i inputs in the coincidence circuit results in 0 and the drive direction is up.

From these examples we see that the beam continues to move after the point of numerical equality is reached. The rest position is one-half cell distant from the point of numerical equality in the direction in which B increases. Thus it is seen that the storage cell boundaries are displaced by one-half cell from the code plate edges. When the Gray code is introduced, it will be seen that the significant advantage of this code is that, at any level, all digits except the one changing remain at full-amplitude readout as the beam is moved beyond match by one-half cell position.

Now we shall develop a generating function for the m inputs, c_m, c_{m-1}, $\cdots c_0$, to the final coincidence circuit. Once we have this generating function in logical notation we can at once set down the block diagram of the logic circuit. We start by observing that, under our rules, the value of any c, say c_k, is determined either by the kth digit pair or by a mismatch in a more significant digit pair. We note that the function $a_k + b_k' = 1$ for $a_k \geqq b_k$, but that $a_k + b_k' = 0$ for $a_k < b_k$.

We can use this function to provide the correct output if the first mismatch occurs at the kth digit. However, our rules say that the most significant mismatch rules. Hence a mismatch occurring at the kth digit of the form $a_k < b_k$; $a_k + b_k' = 0$ must be overpowered by a more significant mismatch of the type $a_m > b_m$, so that the resultant c_k is a 1. To take care of this possibility, we consider all more significant pairs. The function $a_x b_x'$ has the characteristic that it is 1 only for a mismatch condition in which $a > b$. Hence, if we combine all digit pairs for digits more significant than k with a parallel OR circuit, c_k will always be 1 when it is preceded by a mismatch of the type $a_j > b_j$. Finally, we note that $a_j + b_{j'} = 0$ at the first mismatch, for $a_j < b_j$, and that $a_k b_k' = 0$ for all $k > j$. Thus the correct down drive is attained. Our generating function is therefore

$$c_k = (a_k + b_k') + a_m b_m' + a_{m-1} b_{m-1}' + \cdots a_{k+1} b_{k+1}'.$$

The logical circuit realization is shown in Fig. 5. Note that the carry is formed by the long string of OR functions proceeding from the most significant digit towards the least significant digit. For reasons noted earlier, it is necessary to get a version of the comparator in which the position inputs, $b_m \cdots b_0$, in binary code are replaced by position inputs in Gray code, $g_m \cdots g_0$. We first note that any translation operation must translate the Gray-code inputs to the equivalent binary-code inputs, starting with the most significant digit and working down to the first mismatch. However, the translation must not destroy the property that only one digit changes at a time. If the translation has the proper

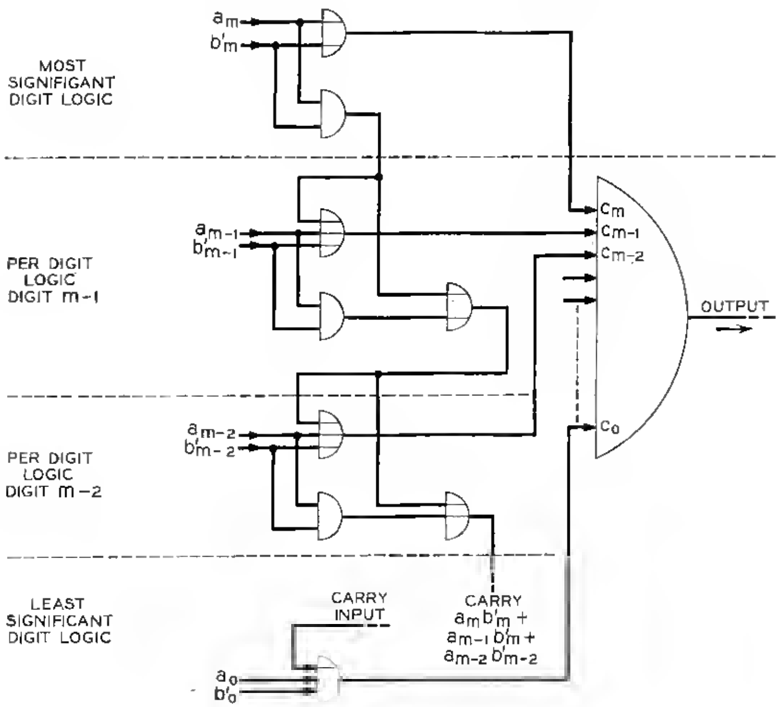

Fig. 5 — Sign-only comparator, binary-binary type.

behavior for match conditions and for the first mismatch, this function may be added to the circuit of Fig. 5, since all c_k for digits beyond the first mismatch are disposed of by the carry which proceeds within the circuit already developed.

To start with, we note that the Gray-code number equivalent to any binary-code number can be generated by applying the following rule in sequence to the digits of the binary number:

$$g_k = b_k \oplus b_{k+1} .$$

The symbol $\oplus$ denotes the "ring sum" or "exclusive or". Its properties are shown by the following table:

b_k	b_{k+1}	$b_k \oplus b_{k+1}$
1	1	0
1	0	1
0	1	1
0	0	0

Now consider the nth digit which is preceded by a match condition. In this case we may write

$$b_n = b_n \oplus b_{n+1} \oplus a_{n+1}$$

since $b_{n+1} \oplus a_{n+1} = 0$, all digits with $i > n$ are matched. In this regrouping we have the term $b_n \oplus b_{n+1}$, which is simply g_n. Therefore we may write

$$b_n = g_n \oplus a_{n+1} .$$

The number formed using this rule provides the correct translation down to and including the first mismatch. This translation also retains the Gray-code property of only one digit change at a time.

As we have noted, this is sufficient. R. W. Ketchledge, who discovered this translation property of the function $g_n \oplus a_{n+1}$, has termed the number formed using this rule a pseudo-binary number. It is the simplest form of translation which allows us to translate a Gray-code number to a form suitable for use in operating the comparator. Its utility can be easily understood if we compare this form to the usual rule for translating from Gray to binary, which involves counting down modulo 2 from the most significant digit to the digit to be translated, a process which clearly involves all of the more significant digits.

Transforming the preceding expression we have

$$b_n' = (g_n \oplus a_{n+1})' = g_n \oplus a_{n+1} \oplus 1 = g_n \oplus a_{n+1}'.$$

This gives us a form eminently suitable for direct replacement in our function c_k. Note that the new c_k has the proper behavior at the first mismatch. Substituting, we then get our new form for c_k:

$$c_k = [a_k + (g_k \oplus a_{k+1}')] + a_m(g_m \oplus a_{m+1}') + \cdots a_{k+1}(g_{k+1} \oplus a_{k+2}').$$

Here we note that the term a_{m+1}' is 1, since all digits in positions of greater significance than the most significant digit are necessarily zero. There we may write:

$$a_m(g_m \oplus a_{m+1}') = a_m g_m .$$

Substituting this into the expression for c_k above results in a form for c_k similar to that for the binary-binary comparator. The logic circuit can be drawn at once from the expression and is shown in Fig. 6.

III. LABORATORY MODEL OF THE FLYING SPOT STORE

3.1 *Application*

The flying spot store discussed in this section was developed to meet the requirements of the electronic telephone switching system described

elsewhere in this issue.[1] The objective was to provide the speed and capacity needed for a realistic test of the laboratory model of the switching system at as early a date as possible, rather than to obtain maximum capacity. As a consequence, many of the desirable features and refinements which can be incorporated in later stores are not included in this model. Nonetheless, it does provide all essential features required for the test.

3.2 *Requirements*

3.2.1 *Capacity*

Because the laboratory model of the switching system serves only a few lines and because feasibility can be demonstrated by setting up a call without providing all of the ancillary routines of a full-sized switching system, the capacity required of the laboratory model of the flying spot store is small, 35,721 bits. Word lengths of 18 and 36 bits are uti-

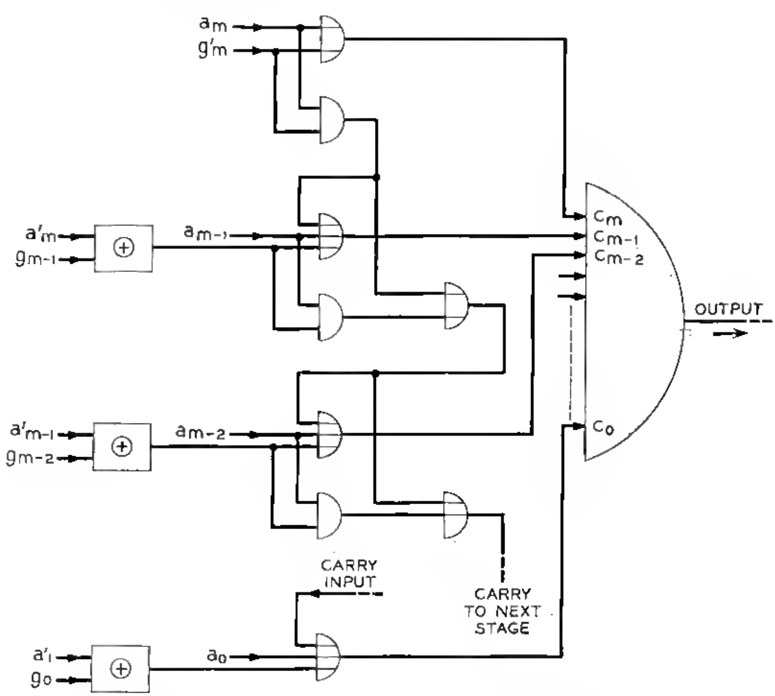

Fig. 6 — Sign-only comparator, binary-Gray type.

lized for this application and the output word is assembled from two or four readouts from the store. The X and Y addresses are each six binary bits. The array size is 64 × 64.

3.2.2 *Mode of Operation*

The laboratory model of the flying spot store has been in operation in the experimental electronic switching system for some time. In this application the store operates in response to input addresses and control signals (orders) supplied by the central control. A block diagram of the store showing input, output and control leads is given in Fig. 7. The output word is assembled in the output shift register from two readouts of nine bits each from the nine parallel storage channels. The central control of the system then takes this word from the output register.

Two main orders are used. These are "advance" and "transfer". In an advance order the word to be read out is located adjacent to the last word read out. This is the order most frequently used in the system. In

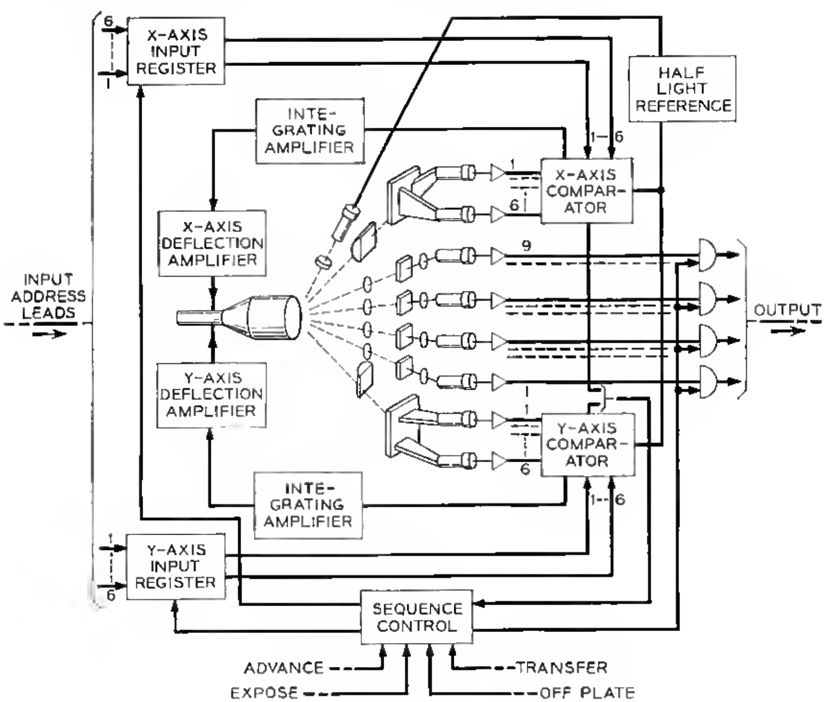

Fig. 7 — Block diagram of flying spot store.

this mode of operation a single signal is supplied from the central control to the advance lead. This signal brings about the following events in the internal program section of the store: The existing address in the x-axis input register is incremented by one. In response to this, the beam is driven to the adjacent location. Once it is there, a sampling signal is generated and applied to the sampling amplifier in each information storage channel. The resulting samples set the flip-flops in the output register. Following this, the internal program shifts the information to the second section of the shift register, again increments the input address register and, after a delay for beam positioning, generates another sampling pulse. The second sampling operation provides the second half of the word.

The transfer order differs in that the word to be read out is located remote from the preceding word read out. In this case the central control furnishes a signal on the transfer lead as well as a complete new address and a greater time is provided before sampling to permit the beam to reach the remote location. Cycle time in this case consists of beam transit time plus the normal sampling cycle time. At the completion of both transfer and advance orders a "cycle complete" signal is generated by the internal program, and sent to central control. In the few instances where the word length is 36 bits, the word is assembled in the central control after two successive readout operations from the store.

In addition to these functions the internal program of the flying spot store also provides special control signals used during plate preparation, line-up and trouble shooting.

3.2.3 *Speed of Operation*

In the laboratory model of the electronic switching system the flying spot store operates at a cycle time of 12 microseconds in the advance mode. This includes the time for incrementing the address register twice, two beam positioning operations and two half-word readouts, plus the assembly of the word in the output register. The maximum time to complete a transfer order is 25 microseconds.

Operating by itself, this flying spot store has performed satisfactorily at a cycle time of 3 microseconds for the advance order and 25 microseconds for the transfer order. In this case, the one-spot beam position change required has been completed in 0.8 microsecond.

3.3 *Components*

Fig. 8 is a rear view of the flying spot store, showing the placement of the various devices.

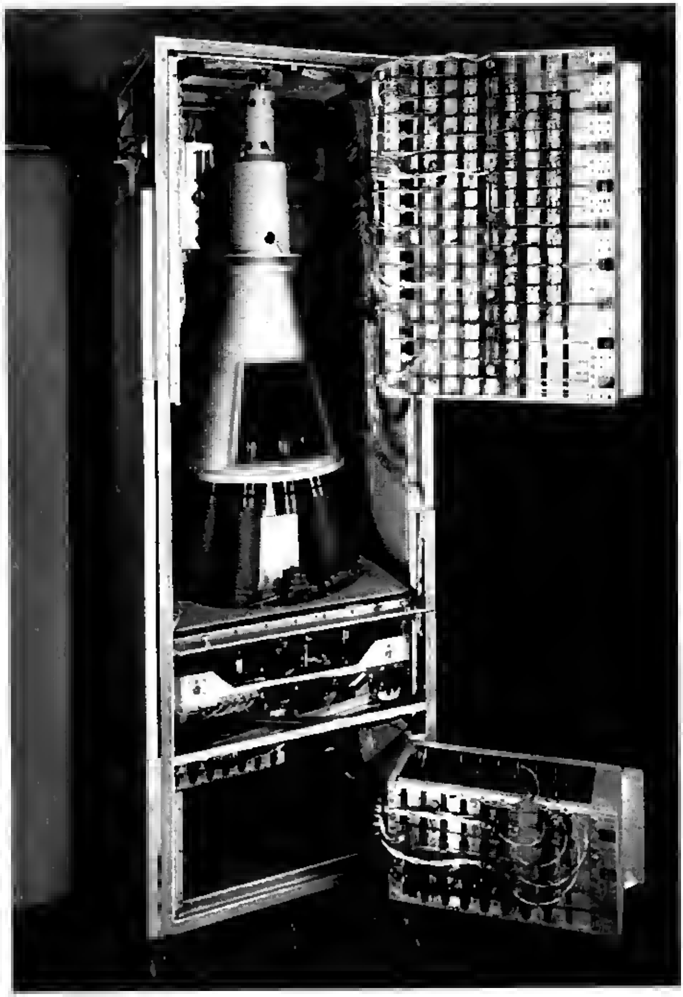

Fig. 8 — View of flying spot store with gates open.

3.3.1 *Cathode Ray Tube*

The cathode ray tube is shown at the top of the cabinet. It is supported above the main casting which holds the lenses, information storage and servo code plates, and is surrounded by a magnetic shield. The tube is 7 inches in diameter and is electrostatically focused and deflected. It is operated at a total accelerating voltage of 10 kv, with a beam current of 10 microamperes to the phosphor screen. The working area on the tube face is 3 × 3 inches. The phosphor used is type P-16. The screen is

aluminized and has a weight of approximately 6 mg per square centimeter.

3.3.2 *Optical System*

The system uses nine Petzval lenses arranged in radial on-axis positions. Four of these can be seen protruding from the body of the support casting in Fig. 8. The storage plates are located within special mounts which are bolted to the main casting. A section of rubber tubing between the end of the lens and the storage-plate mount keeps the system light-tight and dust-free.

The lenses were originally intended for use in a much higher resolution system in which the available flux from each spot on the phosphor screen would have been lower by a factor of 16 or more. In the present application they have been stopped down to $f/13$. This provides greater depth of field and ease of adjustment, as well as reasonable exposure times for the emulsion chosen. The focal length of the lenses is 10 inches, and they are operated at a magnification ratio of 1:2. Thus, the storage area on each plate is 1.5×1.5 inches.

The storage plates are positioned in their mounts in the image plane of the system by three steel pins which bear against two ground edges of the glass photographic slides. A special magazine has been developed which allows a plate to be loaded into the channel for exposure, removed after exposure for development and reinserted after development.

A condenser lens is located beneath the image plane in each channel. This lens images the stop in the objective lens into a circle one-half inch in diameter on the face of the photomultiplier. This lens is required by the point-to-point nonuniformity of the photocathode response, which would introduce additional signal fluctuations into the channel if the narrow beam from the objective lens were to fall directly onto the photocathode.

3.3.3 *Photomultiplier Detector*

A photomultiplier tube is located in each storage channel. The tube used is a 10-stage type, operated with an output current of 350 microamperes in the information storage channels. The total gain required is about 200,000. At the input light level obtained in each channel of this system, the signal-to-shot-noise ratio is high. The discrimination ratio under these conditions is of the order of 10:1, where the fluctuations in the amplitude of the pulses read out from each channel are principally due to phosphor and film nonuniformity and to some regeneration noise

in the photomultiplier tube. Satisfactory operation has been obtained with this signal-to-noise ratio.

3.3.4 *Sampling Amplifier and Output Register*

The output from each information channel photomultiplier detector is connected to a sampling amplifier. This section consists of an equalization and gain stage followed by a sampling stage and output amplifier. Gain is used following the photomultiplier tube output to make the detection of a 1 readout less dependent on power supply voltages.

The sampler outputs are fed to a shift register which is used to assemble the two or four readouts from the store into the word required by the system. The sampling amplifiers are arranged in a ring beneath the information channels. The output register packages are contained in a gate shown in Fig. 8 open at the upper right-hand side of the enclosure.

3.3.5 *Optical Beam Encoder*

The store uses an optical beam encoder of the type shown in Fig. 4. Two cylinder lenses are used, which are not visible in Fig. 8 since they are enclosed within the central part of the casting. They are arranged to provide two orthogonal line images, which fall on a pair of code plates with patterns arranged to give a Gray-code readout of position. A light pipe is provided beneath each column of each code plate to conduct a fraction of the light passing through that column to an individual photomultiplier detector. The light pipes are required because of space limitations on the code plates and the cylinder lens system.

In this type of encoder the length of the line image is made twice the width of the code plate to allow movement of the spot over the entire storage area without loss of position readout in any digit. Consequently, each digit column receives less than $\frac{1}{14}$ of the total light collected by each cylinder lens in the seven-digit encoder provided in this store (only six digits are presently in use). In addition, there are losses in the light pipes. For these reasons, the fraction of the light which must be collected by each cylinder lens is much larger than that which must be collected by each information channel lens. The cylinder lenses used in this system operate at $f/2.8$, with a focal length of 10.0 inches. They are used at a magnification ratio of 1:2.

3.3.6 *Beam Position Servo System*

The readouts from the optical beam encoder photomultipliers are transmitted directly to equalizing amplifiers located directly beneath

them and connected to the digital comparator. The comparator used is the sign-only type discussed earlier. The x- and y-axis comparators are located at the bottom of the enclosure on gates (one is shown at the bottom right in Fig. 8). The error signal resulting from the comparison and code-plate readout drives the integrating and deflection amplifiers which are mounted at the top of the enclosure near the cathode ray tube.

IV. SUMMARY AND CONCLUSIONS

4.1 *System Capacity and Number of Channels*

It has been shown that flux and signal-to-noise conditions must be met in flying spot stores with very high capacity and large number of channels. One important limitation is the maximum flux per unit area which can be obtained from the phosphor screen on the cathode ray tube. With specified maximum tube diameter and flux from the spot, the minimum spot diameter and maximum number of spots in the array on the tube face are fixed. As long as this limitation on the maximum number of spots in the array is not exceeded, maximum system capacity at a constant speed of sampling is not critically dependent upon the number of channels. Therefore, in most applications the number of channels may be chosen to provide word readout, together with error detection and correction bits, in a single-access operation.

System capacity increases with increase in sampling time but, due to resolution limitations on the optical elements and the cathode ray tube, this increase can usually be obtained only by increasing the number of channels.

The flying spot store type of memory is essentially a large-capacity device, since most of the elements must always be supplied and very little equipment is chargeable on a per-channel basis. This nearly fixed bulk of equipment in high-capacity stores means that the number of bits stored per active element in the control and sampling systems can be very large. This is one of the important advantages of this type of memory.

4.2 *Compatibility of Devices*

A very wide range of compatibility exists among the devices used in the store. Thus it has been shown that the emission spectrum of the most efficient fast-decay phosphor available is well matched to the spectral sensitivity curve of the efficient type S-11 photocathode. The efficiency and burn characteristics of this phosphor are such that the

light level required at the photocathode in very high-speed systems can be obtained, even with lenses of high $f/$ number operated at magnification ratios considerably less than unity. The last two conditions permit very wide latitude in the choice of number of channels and result in reasonable tolerances on axial positioning of cathode ray tube, lens and storage plane. Finally, it has been found that the flux level at the photocathode which provides the required signal-to-noise level in readout is sufficient to create a dense image in the film after development, with short exposure times. This permits writing and reading with the same beam.

4.3 *Multiple Channel Organization*

The multiple channel organization permits large-capacity stores to be built without causing any of the devices to operate at the limit of resolution. This reduces the problems in the procurement of devices and tends to increase reliability in the system as a whole. It also provides for maximum possible speed of operation, since the total word is obtained in a single access operation. Some of the multiple channels are used in the optical beam encoder which is the sensor element of the servo. This type of sensor has been shown to be well suited for use in the servo loop. In addition, it introduces a valuable coupling between cathode ray tube and film plane which renders the system less sensitive to mechanical vibration and electrical pickup. Finally, the true independence of stored bits arranged so that only one bit of each word appears in each channel makes the flying spot store ideal for the use of error detection and correction codes.

4.4 *Closed-Loop Beam Positioning Systems*

Closed-loop beam positioning systems have been developed to overcome the analog accuracy problems encountered in open-loop systems. These systems provide digital beam positioning to within one spot diameter of the position for readout, followed by linear servo action in which the beam is locked to one of the code-plate edges of the optical beam encoder. A special digital comparator generates the error signal when the beam is more than one spot diameter distant from the required position for readout; it passes the proportional error signal without modification when the beam is within one spot diameter of the readout location. This comparator meets the special requirements imposed by its being included in the servo loop plus the requirements of the digital number comparison.

Complete systems based on this comparator plus the optical beam encoder are in operation in the laboratory and in the laboratory model of the flying spot store. They provide reproducible beam positioning with an accuracy of ±0.1 spot diameter. Typically, the time to position the beam to this accuracy from a one-spot distance is 0.8 microsecond, and the maximum slewing rate in the region more than one spot distant has been found to be about three spots per microsecond.

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